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PRELIMINARY DATA ON LUNAR SOIL SUPPLIED BY AUTOMATIC STATION "LUNA-16"

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PRELIMINARY DATA ON LUNAR SOIL SUPPLIED BY AUTOMATIC STATION "LUNA-16"

A. P. Vinogradov*

ABSTRACT. Results of preliminary research on a sample of lunar soil obtained by automatic station "Luna-16" are given. Data on the granulometric characteristics of the regolith are given, on its optic properties, types of rock components, and mineral content. The chemical composition is determined for macro- and microelements for various parts of the core sample and for lunar basalt. The isotopic composition of inert gases and several elements is studied. Age according to the Rb/Sr method is determined at 4.25-4.85 billion years.

As is already known [1], automatic station "Luna-16" obtained samples of the lunar soil, taken from the northeastern part of the Sea of Fertility, at a point with coordinates of 0° 41' south latitude and 56° 18' east longitude, approximately 100 km west of Webb Crater (Figure 1, see inset to page 6). /261**

The Sea of Fertility carries traces of relatively quiet subsidence; its shoreline is not framed by a circle of mountains but has a jagged outline. The Sea is a plain with low (100-300 m) branching swells crossing it. There is no radial system of large craters in this section. The lunar soil from the Sea of Fertility characterizes a new region of lunar "sea" surface. Thus,

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**Numbers in the margin indicate the pagination in the original foreign text.

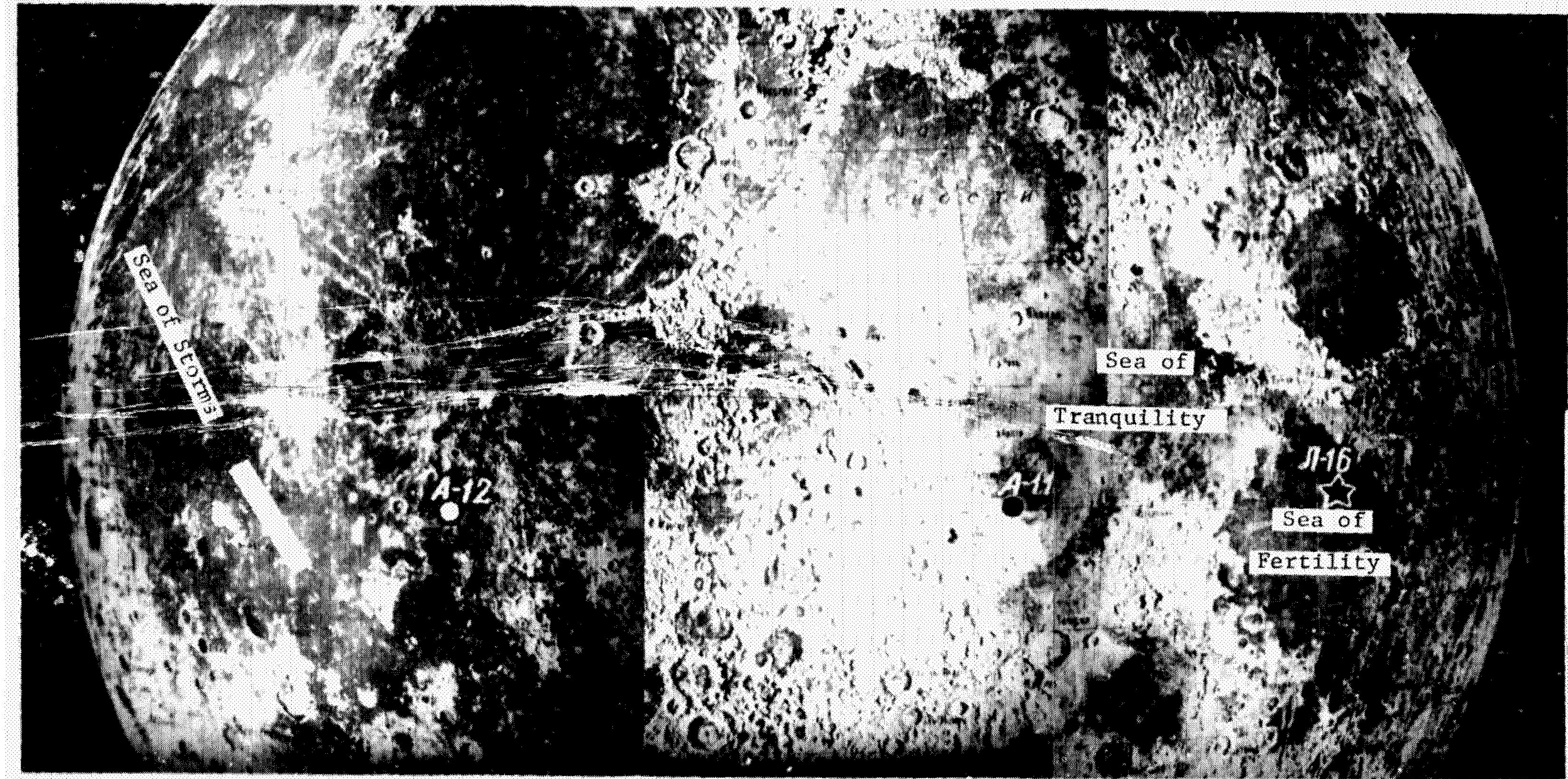


Figure 1. Map of the Moon. ☆ — landing site of "Luna-16";
● — landing site of "Apollo-11";
O — landing site of "Apollo-12";

three vast maria on the visible side located along the lunar equator — the Sea of Tranquility (samples from "Apollo-11"), the Sea of Storms (collections from "Apollo-12"), and the Sea of Fertility (samples from "Luna-16") — make it possible to present a very complete picture of the nature of lunar surface rock.

A drill which dug into the rock to a depth of 35 cm was used to collect the loose surface material of the Sea of Fertility — the regolith. Deeper, it struck hard bedrock or individual large fragments of rock. A core of the regolith filled the drill. The core sample of loose rock — the regolith — was transferred in a helium chamber to the receiving chute. There was no visible stratification, and it seemed homogeneous (Figure 2). Only a small part of the soil at the end face, at a depth of 35 cm, was composed of coarse-grained material. The total weight of the regolith obtained by "Luna-16" was 101 g. The regolith as a whole is an evenly-grained dark-gray (blackish) powder which is easy to form or stick together in separate loose piles. The grains are either fused and rounded off, or angular. Granularity of the regolith increases with depth: average-sized granules of $\sim$ 0.1 mm predominate. The numerical distribution of grains closely corresponds to a power law, which the distribution of particles obeyed in repeated crushing. The median size of grains increased from the surface to the interior of the regolith from 70 to 120 μm. Based on this and on the character of the regolith core sample, several zones can be distinguished: A, B, C, D, and E. The regolith of each zone was studied. Zone A-B is finely-grained material with a small content of /262 a coarse fraction and occupies from 0 to 15 cm of the length of the core sample. Zone C-D is variously-grained material with the inclusion of rock fragments and other particles measuring more than 3 mm. It occupies from 15 to 33 cm of the core sample length. Zone E is a coarse-grained material from 33 to 35 cm of the length (Figure 3).

Thus, the regolith in the Sea of Fertility is not very thick, $\sim$ 35 cm at the sampling point, and possibly reaches 0.5-1 m or more, resembling the thickness of the regolith in the Ocean of Storms, which is assumed to be $\sim$ up to 1-3 m, whereas for the Sea of Tranquility it is assumed to be up to 6 m. We probably do not yet know the true average thickness of the regolith.

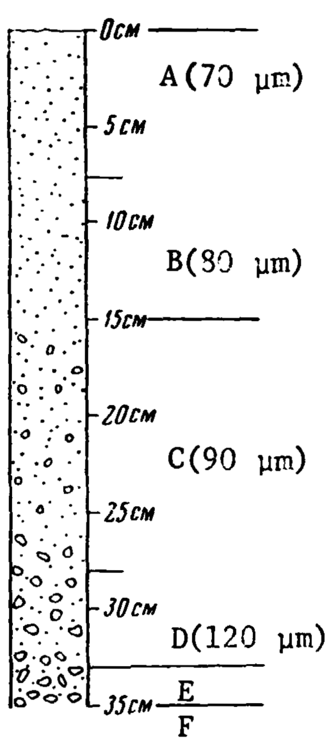
Figure 2. Photograph of the lunar soil in the receiving chute. At the right is the deep part of the core sample; at the end of the chute, the more deeply-granulated material is seen.

A study of physical properties has shown that the regolith has a specific weight in its natural stratification of $\sim$ 1.17 (1.20) g/cm^3.

By mechanical compaction, its density can be brought to 2.3 g/cm^3. Specific heat is 0.17 kcal/kg·degree, heat conductivity is $1.9 \cdot 10^{-3}$ kcal/m·hr·degree, specific electrical resistance is $3.42 \cdot 10^6$ ohm·m, etc. This does not relate to the regolith in natural stratification, but in conditions where the pressure of the surrounding medium is 10^{-5} torr, and the regolith load is 160 kg/k^2.

Optical properties were determined. For the Sea of Fertility, on the average, albedo is 0.069, but in the area immediately around the site where "Luna-16" landed, it is 0.105. Direct determination on the regolith sample is 0.107. Normal albedo is somewhat higher in the red rays: 0.086 in the ultra-violet range, 0.126 in the near-infrared and 0.107 in the visible range of the spectrum. According to the characteristic reflection curve, a mirror component is clearly noted; the angle of maximum light reflection is somewhat greater than the angle of incidence. This is intensified with increased light wave-length and with decreased angle of light.

Basic zones
(Shown is the average size of
fraction particles less than
1 mm)



Fine-grained material with a small content of rough fractions. Fragments of rock larger than 3 mm not included.

Variously-grained material with the inclusion of fragments of rock and other particles measuring over 3 mm.

Coarse-grained material.

Solid bedrock
(or its fragments)

Figure 3. Diagrammatic core sample of lunar soil.

Under microscopic examination, the loose soil of lunar seas, the regolith, exhibits a very contrasting character in comparison with loose Earth soil. Neither is the regolith like ashes from Earth volcanoes. Two basic combinations of particles can be distinguished: basaltic particles of primary magmatic surface rocks, which we noted from the data of automatic station "Luna-10" as far back as 1966 [2], and particles subjected to appreciable transformation on the lunar surface. The first group is characterized by an extremely recent face, observed on Earth only on freshly broken samples of unaltered rocks; they carry practically no traces of rolling and are angular shaped. The second group retains obvious traces of fusion — sintered particles with complex forms, vitrified from the surface, a large number of spherical fused formations — like solidified droplets with a vitreous or metallic face, similar to "cosmic globules" on Earth. These particles indicate that they were formed from liquid and quickly solidified. Figure 4 shows regolith particles under the microscope, and in Figure 5, various particles are collected into groups: gabbro, basalts, anorthosites, breccias, various particles (see also Figure 6). The scanning electron microscope shows (Figure 7, 8) that large silicate particles are covered with a fine fraction of other particles. The content of various particles in a regolith fraction of +0.45 mm is shown in Table 1.

Particles of basaltic rock are of at least two types which characterize the solidifying conditions of the basaltic melt — fine-grained basalts (with glass) and coarse-grained basalts of the gabbroid type (Figure 9). They have an ophitic structure and form one fourth of the entire coarse-grained fraction (over 0.45 mm). The basic minerals of these rocks are plagioclase, pyroxene, ilmenite, and more rarely, olivine. Their relative content varies considerably in different particles. Thus, we can now say that a volcanic process took place on the Moon, with eruption of basalts, and evidently, formation of the lunar crust, whose exact thickness we do not yet know.

In our opinion, this universal process of eruption of easily-fusible material from the depths of the Moon (with degassing) proceeded by zone fusion. /264
Feldspar rocks (anorthosites) and white crystalline grains are also encountered.

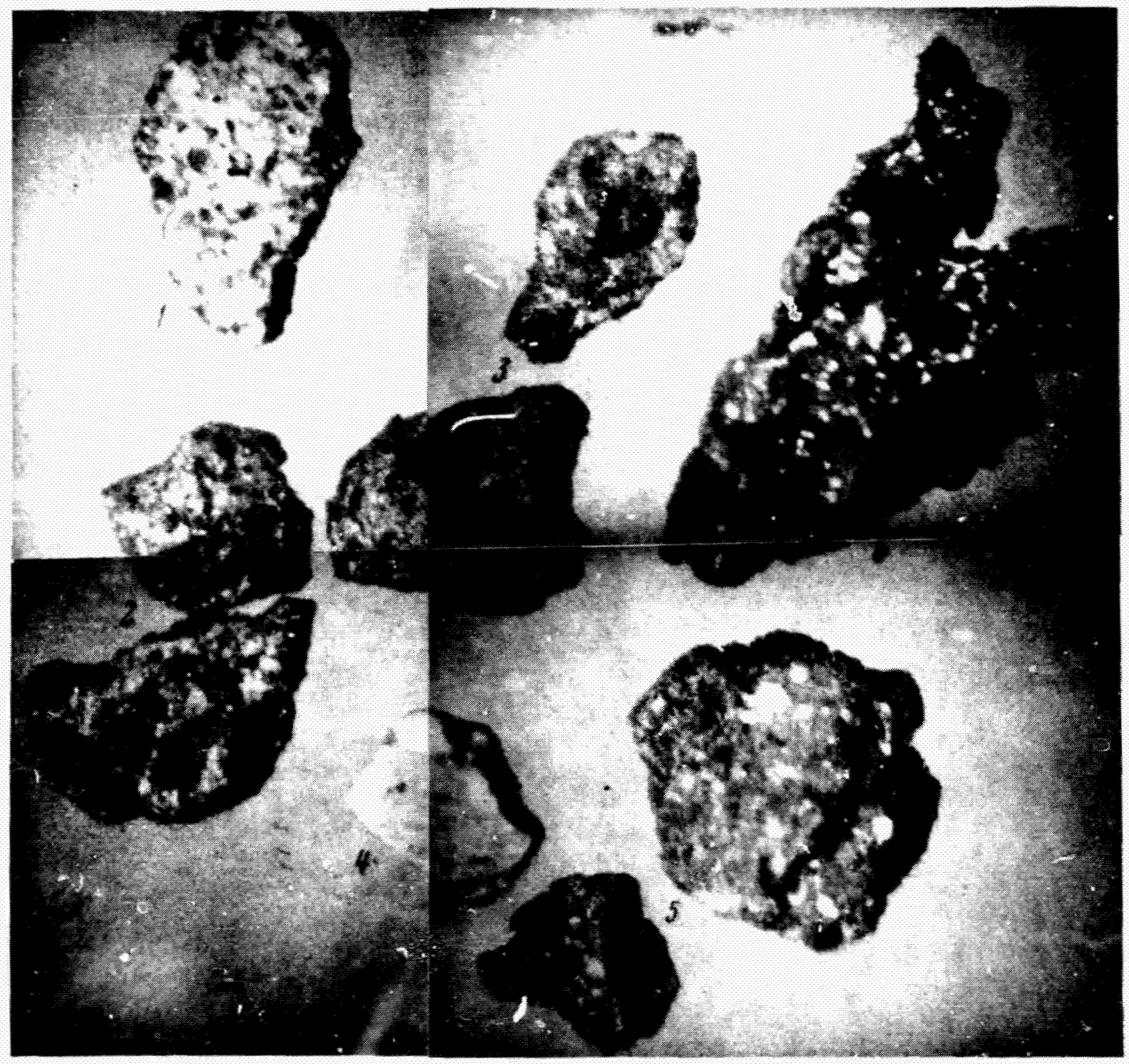


Figure 4. Coarse particles of lunar rocks.

1 - coarse-grained basalt (gabbro) light; 2 - coarse-grained basalt (gabbro) dark; 3 - basalts, partially porous; 4 - snorthosite; 5 - breccia; 6 - slaggy fused particle.

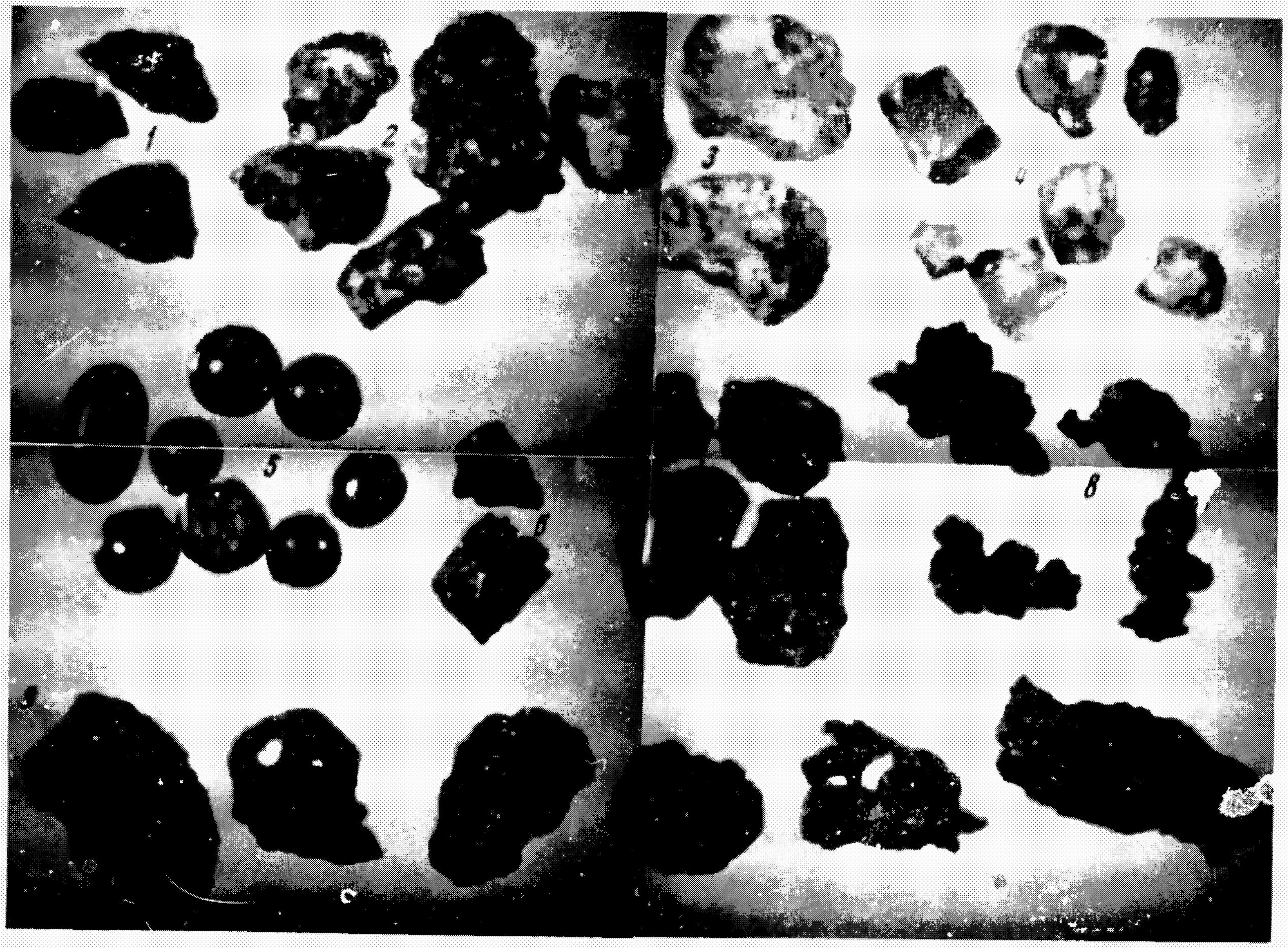


Figure 5 Groups of the most characteristic particles of the lunar regolith from the +0.45 mm fraction.

1 - basalt; 2 - coarse-grained basalt (gabbro); 3 - anorthosites; 4 - homogeneous glass and mineral grains; 5 - globules and spherical formations; 6 - reddish-brown glass; 7 - breccia; 8 - sintered particles (sinters); 9 - slags and fused particles.

Figure 6. Various kinds of particles: globules and spherules, glass, slag.

Figure 7. Picture of fine fraction particles of the regolith, obtained in a scanning electron microscope in secondary electrons. Coarse silicate particles are covered with finer particles.

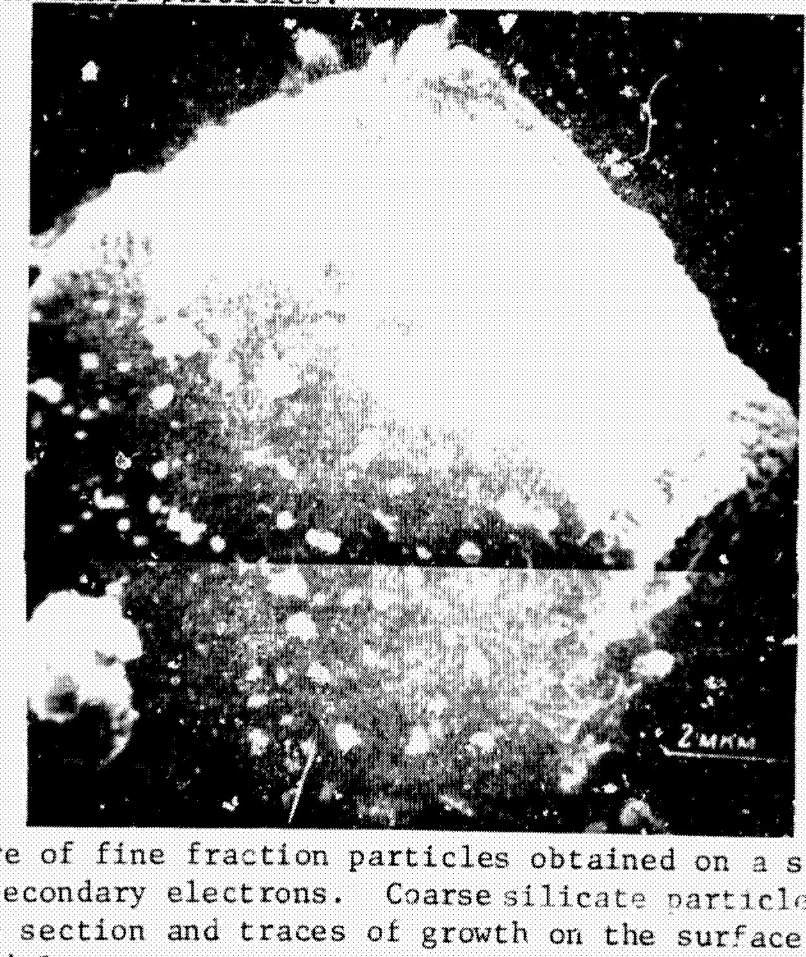


Figure 8. Picture of fine fraction particles obtained on a scanning electron microscope in secondary electrons. Coarse silicate particles with a near-hexagonal cross section and traces of growth on the surface dusted with very fine material.

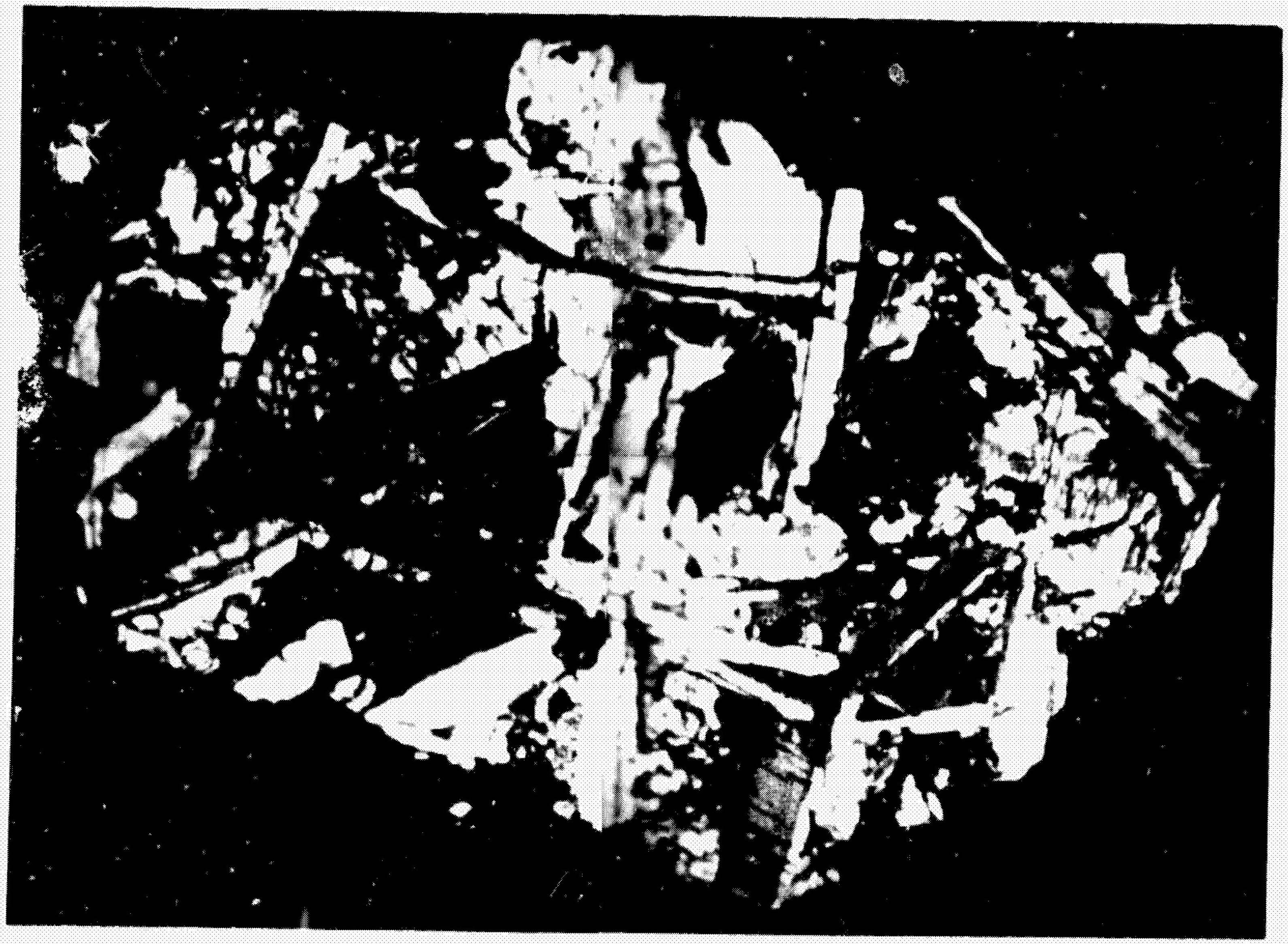


Figure 9. Thin section of coarse-grained basalt (gabbro) in polarized light (enlarged). Idiomorphic grains of plagioclase and ilmenite (pa tially), xenomorphic pyroxene and a few deposits of olivene.

TABLE 1. DISTRIBUTION OF PARTICLES OF VARIOUS ROCKS IN +0.45 mm FRACTION IN ZONES A, B, C, D, NUMERICAL %

Rock	A	B	C	D
Gabbro	13.1	17.5	8.1	15.2
Basalt	7.3	9.0	4.9	7.9
Anorthosite	1.1	3.7	2.5	4.5
Breccia	33.9	41.4	35.5	8.3
Slag and sinter	40.0	17.5	21.8	53.5
Glass and single grains	2.3	4.0	6.2	6.1
Spherules	1.2	1.3	1.2	1.6
Various particles	1.2	5.7	---	2.6
Total number of particles, pieces	838	297	2351	755
Weight of fraction, g	0.230	0.100	0.560	0.260

Their content is unknown. Their origin on Earth is also not very clear.

Breccia is cemented, lithified rock, formed as a result of the compaction of finely divided regolith material and containing, in various proportions, all the components, including particles of primary magmatic rock, nickel-iron alloy, etc. In some breccia, a rolled form of particles is noted, and sometimes weak compaction, which makes them easy to crush. Magnetic breccia comprises up to 40% of the total number of particles.

Slag and sinter are fine caked particles, forming very complex, uneven branched aggregates. They are composed of all regolith components.

Glass is vitrified and scorified particles. In general, at least half of all regolith particles are fused or scorified on one or several sides. Depending on composition (Fe or Ti content, etc.) they have various colors — from dark greyish brown to black tones. Both vesicular slag-like fusion and smooth glazed vitrification are encountered. This is typical lunar fusion, occurring in the instantaneous heating of a basically cold particle.

Solidified drops are globules or similar formations. Various shapes of globules are encountered — pear-shaped, dumbbell-shaped, etc. — and various colors — transparent, cloudy-white, greenish, yellowish brown, opaque, often hollow. Their sparkle ranges from glass to metallic. Their number increases in fine fractions. They are formed at temperatures much higher than the temperature at which rocks melt, when they are sprayed in a molten state.

However, grains of separate minerals are noted: plagioclase, olivine, anorthite, pyroxenes, spinels, ilmenite, iron particles. We shall return to nickel-iron particles in the regolith later. The content of various minerals in the regolith is given in Table 2. We see that the olivene content is quite significant and resembles that in the regolith samples of "Apollo-12", whereas, the olivine content in samples from "Apollo-11" is much lower. The ilmenite content, for example, is close to that in samples from "Apollo-12", whereas, in samples from "Apollo-11" it is much higher than in samples from "Luna-16" or "Apollo-12". Olivine is found in the regolith only in the form of separate uneven single-crystal fragments (acute-angled pieces), variously colored, as /265 well as in gabbro particles. X-ray photographs indicate no lattice deformation or twinning effect, i.e., no lattice stress. This is the ordinary alpha-modification of olivine, and is characterized by disordered distribution of magnesium and iron atoms in the structure. As seen from micro X-ray spectral analysis of a similar silicate particle, it has the following composition (weight %):

TABLE 2. MEASUREMENT RESULTS OF MESSBAUER SPECTRUM OF LUNAR MATERIAL

Mineral	Proportion of the total area of the Messbauer spectrum of iron-containing mineral, %				
	Soviet measurements			USA ("Apollo-11")	
	A3	A7	Gb. + 0,20 —0,45	84-14	45-24
Ilmenite	7,7	6,7	9,2	19,7	26,9
Pyroxene	69,0	71,5	65,1	67,6	60,8
Olivine	18,8	16,7	25,5	4,4	6.1
Iron	4.5	5,1	not counted	5,8	2.1
Troilite	⩽1	⩽1	⩽1	⩽1	⩽2
Magnetite	⩽2	⩽2	⩽2	1,4	2,1

SiO_2	36,0
MgO	27,5
FeO	33,8
CaO	0.38
MnO	0.29
Cr_2O_3	0,15
Al_2O_3	0.05
TiO_2	⩽0,01
CoO	0,03
NiO	<0,01
Σ	98,2

This homogeneous crystal of olivine, whose ferruginosity is 40 mol % Fe_2SiO_4, also has the molecular formula:

$$[Mg_{1.14}\ Fe_{0.79}(Ca,\ Mn,\ Cr)_{0.02}]\ SiO_4.$$

The most widespread mineral in the regolith is anorthite, followed by augite and ilmenite. Anorthite is encountered in the form of fine-grained aggregates in samples of basalt, gabbro, globules and in a regolith fine fraction. Isolated single-crystals are not found.

Plagioclase is also found in the form of triclinicly symmetrical single crystals. Augite-pigeonite types of pyroxene are encountered in pieces of rock where in a number of cases they play an important role in gabbro basalts. X-ray spectral analysis was used to study the distribution of elements in thin sections of basalt which helped identify the minerals (Figure 10).

Ilmenite appears in the bulk sample of regolith, sometimes intergrown with augite. Chrome spinel appears in the form of dark-colored single crystals. Concerning magnetic material, micro X-ray spectral analysis of sample 3-4b can be cited. Surface analysis (without preparing a thin section) indicates uneven distribution of Fe, Ni, Cr, Ti, Si, Al, Mg, and Ca. Zones with rock-forming elements are distinguished, as well as zones with increased concentrations of Fe and Ni — Fe $\sim$ 6% and Ni $\sim$ 1%. At several points, iron content to /267 66% and nickel to 6% are observed. However, Messbauer spectrocopy did not succeed in finding nickel in magnetic particles. X-ray analysis of iron particles detected alpha-iron, i.e., kamacite. Taenite was not detected. The volume of iron particles in the regolith is less than 1%. It is difficult to say anything definite now about the occurrence of these particles. As we shall see further, the amount of nickel in the regolith, in comparison with monolithic rock (basalts) increases, in the case of data from "Luna-16", as well as "Apollo-11 and -12", on the average, by five times, but cobalt — only 1.5 times the maximum. Moreover, we see a very small platinoid content in the regolith, whereas in iron meteorites it is many hundreds of times greater than in rock. A chemical analysis was made simultaneously by X-ray spectral (chiefly of the basic elements), mass spectral (all the elements), spectral and activation methods — selectively for separate elements (Table 3).

As we see, variations of the main composition of the regolith on the four levels are insignificant. Much more notable are the differences of compositions between the regolith and basalt rock. If we compare the composition of rock from "Luna-16" with lunar rock samples from "Apollo-11 and 12", the

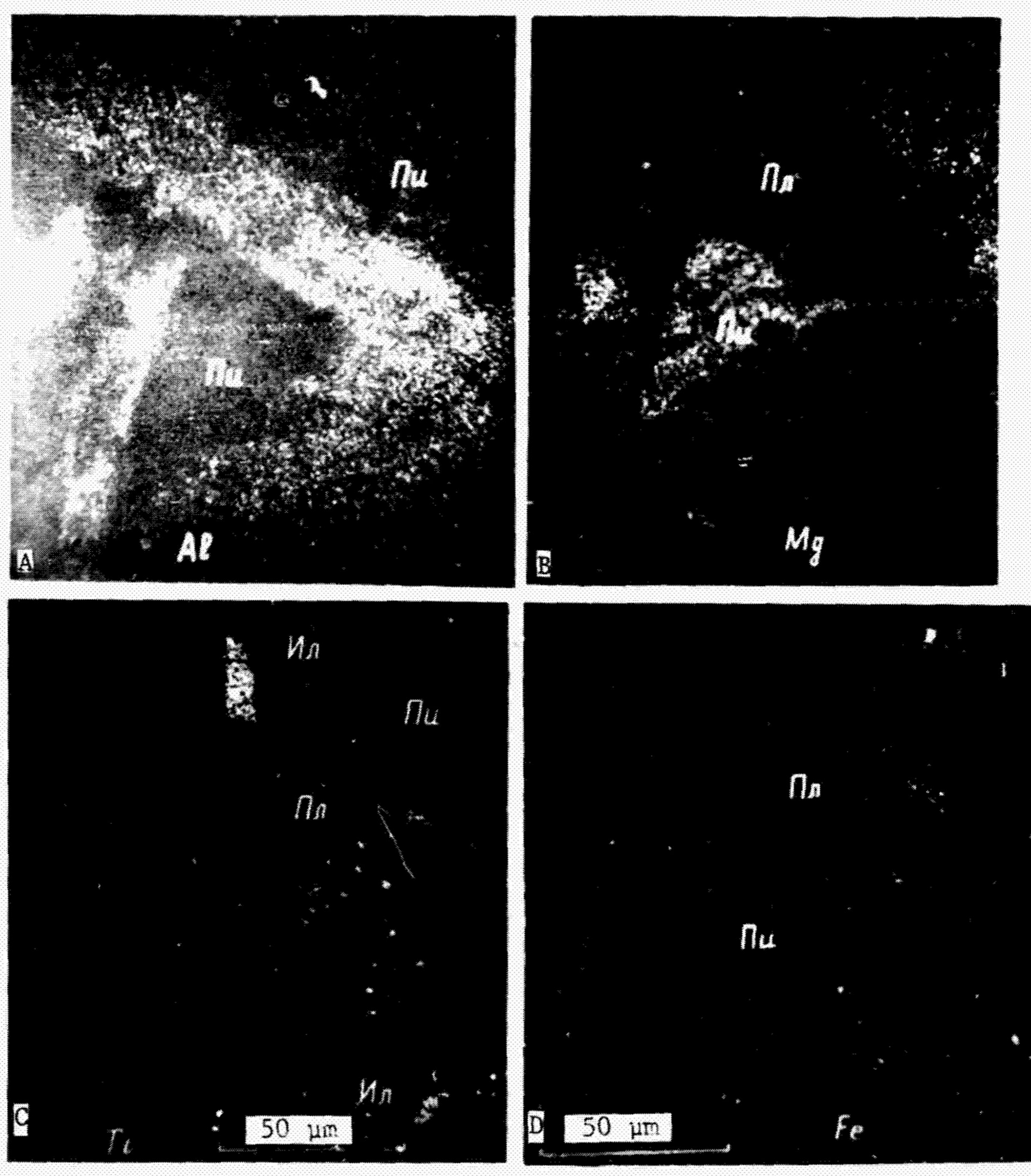


Figure 10. Photograph of part of a thin section of basalt (gabbro), obtained in an X-ray microanalyzer.

Distribution pattern: a - aluminum; b - magnesium; c - titanium; d - iron. Minerals: Пи — pyroxene; Пл — plagioclase; Ил — ilmenite.

differences as a whole are also small, with the exception of Ti and Zr content, and several other chemical elements found in small quantities in lunar rock (microelements) (Table 4).

We must note the high content of F, S, Cl and other volatiles which have dissipated from the Moon. However, vacuoles have been detected in regolith particles possibly containing common gases; these are being investigated. /268

Comparison of the chemical composition of the regolith and monolithic rock in the three maria indicates that the material is the same everywhere, with variations of composition both in the regolith and in monolithic rock. The largest difference in the composition of rocks from "Luna-16" is in the low Ti content. It is practically identical with rock from the Ocean of Storms ("Apollo-12") or almost half as much as in the Sea of Tranquility. Variations in the content of Mg and Fe are small (Table 5).

The largest amount of Zr is noted in crystalline rock from the Sea of Tranquility where there is much Ti, Y and Sc. The content of the majority of macroelements, as well as Ni and many microelements, is practically identical in the three maria. Of much greater interest are the differences in composition of the regolith and native rock in the same sea. These differences recur in all three maria. For example, the content of Fe, Ti, and Zr is always higher in native rock than in the regolith. Ni content is always higher in the regolith than in crystalline rock. The conformity of Ti contents in crystalline rock and in the regolith indicates that the regolith was formed in place and not introduced from somewhere else (as volcanic ash). The quantity of Ca and Al_2O_3 increases in the regolith. Thus, the regolith is rich in plagioclase and poor in pyroxene, olivine, ilmenite (and spinel); i.e., crystalline rock is more mafic than the regolith. Rare lithic elements are most often contained in crystalline rock from the Sea of Tranquility — Y, TR, Zr, Sc. This also relates to Th and U (Table 6). /269 /270

We have already noted the low content of platinoids and gold in the regolith. There are still few data in this area, but the following

TABLE 3. MICROELEMENT CONTENT IN REGOLITH FRACTION OF ZONES A, B, C, D, WEIGHT %*

Component	Regolith A	Regolith B	Regolith C	Regolith D	Basalt
SiO_2	41,7	41,2	42,5	41,3	43,8
Al_2O_3	15,32	15,40	15,45	15,15	13,65
FeO	16,80	16,55	16,30	16,90	19,35
CaO	12,20	12,80	12,42	12,55	10,40
MgO	8,73	8,82	8,96	8,60	7,05
TiO_2	3,39	3,46	3,30	3,42	4,90
ZrO_2	0,015	—	0,013	—	0,04
Cr_2O_3	0,31	0,25	0,30	0,26	0,28
MnO	0,21	0,20	0,20	0,22	0,20
Na_2O	0,37	0,36	0,36	0,28	0,33
K_2O	0,10	0,12	0,10	0,10	0,15
S	0,19	0,20	0,18	0,25	0,17

*X-ray spectral method

TABLE 4. MICROELEMENT CONTENT IN ROCKS FROM "LUNA-16" (MASS-SPECTRAL AND SPECTRAL DETERMINATION), PARTS PER MILLION

Element	Regolith A	Regolith B	Regolith C	Regolith D	Basalt	Element	Regolith A	Regolith B	Regolith C	Regolith D	Basalt
Li*	--	10	—	10	—	Cd	1	0,75	1	1,2	—
Be*	—	2,8	2	2,7	--	In	0,06	0,025	0,086	0,08	—
F	265	292	246	277	181	Ba	42	259	57	48	206
B	4,5	3,9	6	4,6	5	Sn	0,6	1,4	—	2	4
P	—	254	—	200	511	Sb	0,4	0,3	0,7	0,35	0,5
Sc	27	33	23,3	25	20	Te	0,2	---	0,15	0,2	—
Cl	66	74	36	72	--	W	-	4,7	5,5	7,5	9
V	64	73,5	55,3	55	42,5	Au	0,0065	0,0043	0,0063	—	--
Co	68	56	44	61	29	Tl	0,3	0,2	—	0,5	—
Ni	190	137	250	178	147	Pb	6,4	6,6	7	6	7,7
Cu	36	39,8	35	56	13	I	0,15	—	0,26	0,14	—
Zn	10	20	33	21,5	25	Y	45	46	50	56	58
Rb	3	6,3	5,5	--	—	La	7,3	8	7,4	7,2	7,[illegible]
Sr	90	156	—	182	445	Ce	21	26	24	23	24,6
Cs	0,06	0,26	—	0,08	0,75	Pr	4,5	4,7	4,6	4,5	[illegible]
Zr	350	334	354	346	—	Nd	20	28	21	23	25
Hf	1,1	3,6	1,2	1	0,3	Sm	5,6	6,8	6,2	6,8	7,1
Mo	7	12	3,6	5	1,2	Eu	1,6	1,2	1,3	1,1	1,2
Ga	11	—	4,9	—	1,2	Gd	6,0	4,7	4,6	5,8	4,5
Ge	1,3	1,2	1,2	1,5	2,5	Tb	0,75	1,0	0,9	0,9	0,9
As	0,4	0,56	0,6	0,3	2,9	Dy	5,0	5,3	5,0	5,0	5,2
Se	0,45	0,5	—	0,4	0,7	Ho	2,0	2,2	1,9	1,8	2,0
Br	0,26	0,27	0,24	0,33	1,3	Er	5,0	5,0	5,0	4,7	5,0
Ru	0,03	0,044	0,01	—	6	Tm	0,4	0,4	0,4	0,4	0,4
Rh	—	0,0037	—	—	--	Yb	3,5	3,6	3,5	3,5	3,6
Pd	0,0086	0,012	—	0,01	0,027	Lu	0,28	0,3	0,3	0,3	0,3
Ag*	0,05	0,059	0,02	0,07	0,2						

*spectral determination

TABLE 5. COMPARISON OF THE CONTENT OF THE REGOLITH AND CRYSTALLINE ROCKS FROM THE THREE SEAS

(macroelements, %; microelements, parts per million)

Component	Crystalline rock			Regolith		
	Sea of Tranquillity, Coll. by "Apollo 11"	Sea of Storms. Coll. by "Apollo 12"	Sea of Fertility. Coll. by "Luna-16"	Sea of Tranquillity. Coll. by "Apollo 11"	Sea of Storms. Coll. by "Apollo 12"	Sea of Fertility Coll. by "Luna-16"
SiO_2	41	40	43,8	43	42	41,7
Al_2O_3	12	11,2	13,65	13	14	15,33
TiO_2	10	3,7	4,9	7	3,1	3,39
FeO	19	21,3	19,35	16	17	16,64
MgO	8	11,7	7,05	8	12	8,78
CaO	10	10,7	10,4	12	10	12,49
Na_2O	0,5	0,95	0,38	0,54	0,4	0,34
K_2O	0,12	0,065	0,15	0.12	0,18	0,10
MnO	0,4	0,26	0,20	0,23	0,25	0,21
Cr_2O_3	0,6	0,55	0,28	0,37	0,41	0,28
ZrO_2	0,1	0,023	0,04	0,05	0,09	0,013
NiO	(0,007)	—	0,04	0,03	0,025	—
Rb	2,5	0,64	—	2,2	3,2	5,9
Ba	90	72	206	68	420	114
Sr	110	145	445	90	170	169
Yb	2,5	—	3,5	2,5	—	3,5
Y	250	51	54,0	130	130	58,0
Zr	700	170	300	400	670	347
V	45	88	42,5	42	64	61
Sc	110	50	20	55	47	27
Ni	55	54	147	250	200	190
Co	9	4[illegible]	29	18	42	53
Cu	5	—	13	—	—	37
Li	15	5,[illegible]	—	15	11	10*
Ga	6	—	11	—	—	4,9

*spectrally, all the rest — mass-spectrally

distribution of platinoids and gold in lunar rocks can be seen (Table 7).

All rare earths have not yet been determined. The isotopic analysis of Li^7/Li^6 for the regolith is 12.28; K^{39}/K^{41} is 14.00 ± 0.18; for Rb^{85}/Rb^{87} (for average sample) 2.57 ± 0.04, i.e., isotopic composition corresponds to

TABLE 6. CONTENT OF Th and U, PARTS PER MILLION

Element	Regolith			Crystalline rocks		
	"Apollo-11"	"Apollo-12"	"Luna-16"	"Apollo-11"	"Apollo-12"	"Luna-16"
Th	2,24±0,06	6.0±0.6	0.474±0,05*	2,9±0.4	0,88±0,09	1,14±0,1*
U	0,59±0,02	1,5±0.2	0,1±0,01*	0,7±0,1	0,24±0,035	0,2±0,02*
Th/U	3,8	4.0	4,7	4,0	3,7	5,7

*determined by the mass-spectral method.

TABLE 7. DISTRIBUTION OF PLATINOIDS AND GOLD IN LUNAR ROCKS, PARTS PER MILLION

Rock	Pt	Pd	Ir	Ru	Rh	Au
Earth basalts	0,02	0,02	—	—	—	0,004
Crystalline lunar rocks:						
Coll. by "Apollo-11"	— —	0,006*	0,0001—0,01	—	—	—
Coll. by "Apollo-11"	—	0,1**		—	—	0,0016****
Coll. by "Apollo-12"	—	—	0,0013***	—	—	0,0011***
Coll. by "Luna-12"	—	0,027	—	6,3	—	—
In the regolith:						
Coll. by "Apollo-11"	—	0,04**	—	—	—	0,0021****
Coll. by "Luna-16"	—	0,01	—	0,027	0,0037	0,002
In iron meteorites:	12,0	3,7	2,8	—	—	1,0

* Baedecker, Wasson. Sci., Vol. 167, No. 3918, 1970.
** Morrison et al. Sci., Vol. 167, No. 3918, 1970.
*** Laul, Keays, Ganapathy, Anders. Earth a. Planetary Sci. Letters, Vol. 9, No. 2, 1970.
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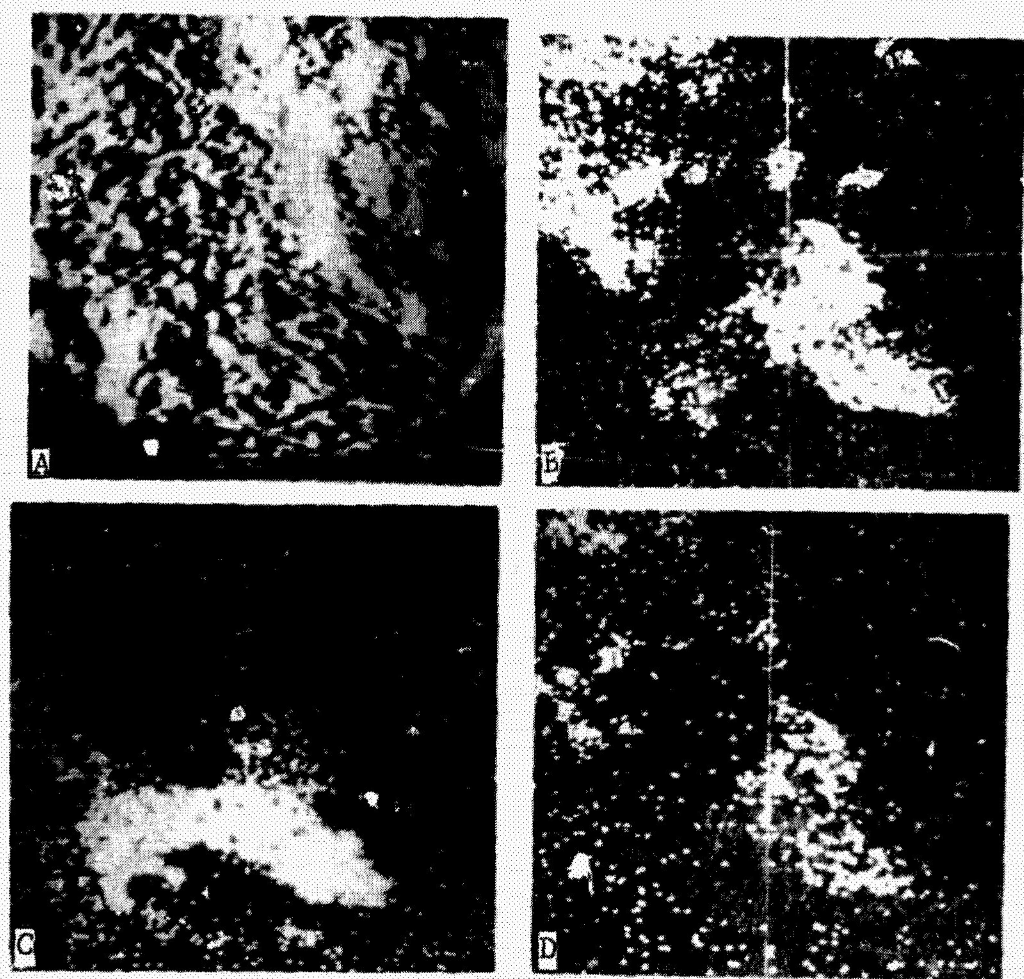

Figure 11. Scanning images of a magnetic particle, recorded in an X-ray microanalyzer.

A - image in absorbed electrons; B - distribution pattern of iron; C - silicon; D - nickel.

the isotopic composition of these elements on Earth. At the same time, for example, for lithium, disturbances of isotopic composition in meteorites have been observed.

As is known, shearing products develop under the influence of solar wind. They were detected in the regolith — Na^{22}, Al^{26}, etc. For example, Al^{26} gives 173 ± 113 dec/min·kg. This work is continuing, and we would like to have data for both fraction zone A and for fraction zone D of the deeper part of the regolith core sample. This would explain many things.

It is not without interest to note that the infrared spectrum of the regolith indicates the presence of a wide structureless absorption band in the region of silicon-oxygen bond fluctuations. Annealing the regolith specimen in an argon atmosphere to 1000° C leads to the appearance in the infrared spectrum of a distinct structure — separate bands connected with the absorption of isolated and compound SiO_4-groups, silicates, etc. Consequently, it can be assumed that the regolith material has been irradiated, and possible changes developing as a result are removed by annealing.

Solar wind affects the rock, causing the formation of shearing products at shallow depths — 3-5 cm. Therefore, we decided to measure the induced activity both in the upper layers of the regolith and at its base. Results could explain the history of the regolith buildup.

The regolith contained inert gases of unusual composition, whose content did not depend on the depth of the regolith (the regolith sample was related to zone D) (Table 8).

TABLE 8. CONTENT AND ISOTROPIC COMPOSITION OF INERT GASES IN SAMPLES OF DUST, $10^{-8} \cdot cm^3$ /271

Isotopes	Sea of Fertility, sample 17	"Apollo-11"		
		Schaffer, Zahringer	Reynolds	Hintenberger
He^4	18 000 000	11000000—19000000	29 000 000	9 000 000
He^4/He^3	2670	2540	2130	2770
Ne^{20}	340 000	313 000	530 000	125 000
Ne^{20}/Ne^{22}	12,80	12,4	12,85	12,6
Ne^{21}/Ne^{22}	0,00332	0,0340	0,00332	0,0352
Ar^{40}	53 000	38 500	57 000	56 000
Ar^{40}/Ar^{36}	0,[illegible]	1,1	1,126	3,04
Ar^{36}/Ar^{38}	5,26	5,20	5,19	5,08
Kr^{84}	22	21	37	8,5
Xe^{132}	8,5	10	4,6	2,2

Solar wind gases are the dominant element of the gases. Their composition differs greatly from the composition of gases on the Earth and those of meteorites. The concentration of the gases is very high, several orders of magnitude higher than on the Earth or in meteorites. The He and Ne content corresponds with their content in several meteorites rich in inert gases. The isotopic composition of Ar differs especially — for example, $Ar^{40}/Ar^{36} \sim$ ~ 1, but $Ar^{36}/Ar^{38} \sim 5.25$ corresponds to Earth. The quantity of Ar^{40} is 4-5 times greater than its quantity would be if it were formed in rock as a result of the decay of K^{40}. Isotopic composition of Xe also differs from the terrestrial composition and is being studied further. The inert gas content of the material from the Sea of Fertility is close to that in the regolith of the Sea of Tranquillity. First determinations of the age of the Moon were obtained by the Rb/Sr method, primarily for the fine regolith fraction, which indicated $4.85 \cdot 10^9$ years $-4.25 \cdot 10^9 \pm 0.27 \cdot 10^9$ years. The isochronous average is 4.45 and $4.65 \cdot 10^9 \pm 0.5 \cdot 10^9$ years. Thus, the samples from the three maria are very close according to absolute age, i.e., the age of the Moon corresponds to the age of the Earth. The same values are obtained by Pb^{206}/Pb^{207}. Age is difficult to calculate by the K/Ar method. The exposed age of the regolith is of special interest.

Thus, the lunar rocks from the three maria are of one general type — basalts — and their composition variations depend on the conditions of their melting, but from the regolith a somewhat different story follows.

Rock from the Sea of Fertility, as we see, is close to the composition of rock from the Ocean of Storms. However, for example, in terms of content of inert gases in the regolith, it is close to the regolith of the Sea of Tranquillity, etc.

Let us turn to several preliminary considerations. It is still premature to express a definitive opinion on processes on the lunar surface. We will confine ourselves to data obtained in studying rock samples from "Luna-16" from the Sea of Fertility, and naturally, we will compare them with data obtained in the flights of "Apollo-11 and 12". Material from all three maria — the Sea of Tranquillity, the Ocean of Storms and the Sea of Fertility — are remarkably similar in petrological, mineralogical and chemical composition, although details differ. The huge lunar maria located along the Moon's equator are depressions once flooded with basic lava. At some long past time, in the age of intensive volcanic action, a large mass of basaltic rock was poured out onto the surface of the Moon, accompanied by the dissipation of gases. Depending on conditions of eruption, depth, temperature, etc., a certain variety of the common basaltic surface rock of the Moon was created, according to the content of Fe, Ti, Zr, Ba and other elements. The ferruginosity of magma is not of definitive importance in this endogenous process. It is possible to find rocks derived from basalts (anorthosite, riolite, etc.). We still do know the thickness of the basalt crust of the Moon. /272

The absolute age of the lunar surface rocks, more accurately the age of the Moon, corresponds almost exactly to the age of the Earth. Lunar seas are covered with a regolith layer. Its thickness evidently varies considerably, and at the sampling point in the Sea of Fertility for "Luna-16" it was not more than 0.5 m. Variations are probably within a few meters. The regolith, as we have already seen, is a nonhomogeneous mixture of grains of rock, minerals of various size, form and color, both fused and angular particles. In depth, the relation between various granules varies, although any kind of stratification of the material is not noted. This material is the result of rocks being crushed at high temperatures, which is responsible for the formation not only of fused regolith particles, but also the formation of spheroids. The regolith is not like the volcanic sand of volcanoes on Earth. The composition of the regolith, as we have seen, differs somewhat from that of lunar crystalline rocks. It contains a lesser amount of mafic elements. It should then be more easily fusible than primary basaltic rock. Before touching the problem of the formation of the regolith, let us recall the basic factors of lunar "weathering". They are, first of all, temperature fluctuations of lunar surface rocks from the lunar day to lunar night for billions of years — a temperature range $\sim \pm 100°$ C. Then there is radiation of the surface rocks of the moon by solar wind and galactic cosmic rays - also the vacuum in which the lunar rocks exist and, finally, possible meteorite impacts. Probably the temperature fluctuations of the lunar surface rocks somehow affect their strength, but we cannot evaluate that now. Solar wind and galactic radiation have a considerable effect. First of all, on the basis of our observations, it would follow that the whole regolith will show signs of the effect of solar wind to a depth of 35 cm. In the sample from zone D, the regolith contains a huge amount of solar inert gases. Then, the infrared spectrum of the regolith shows signs of its radiation. Finally, we must certainly expect radioactive shearing products to be determined from deep regolith layers. This gives preliminary indications that either the regolith was mixed in place or that the history of its formation is written in layers there.

Radiation does not penetrate deeply — it reaches the first several centimeters of soil. On the basis of observations and study of the so-called metamycality(sic) in minerals composed of radioactive elements, it follows that they lose strength, their crystal lattice is deformed, etc. However, this does not usually lead to complete disintegration of the minerals. We have tried to detect metamycality in particles of the regolith. Moreover, radiation begins its work mainly when the material is already crushed. Therefore, solar wind does not play a leading role in the process of crushing the material during regolith formation (its fusion), but affects the strength of the material. Usually, the formation of lunar maria and, therefore, primarily the formation of the regolith which fills them, is connected with the action of falling meteorites, with impacts. It would be interesting to describe the fall of clusters of meteorites on the side of the Moon facing the Earth in the region of present-day lunar maria located along the equator. Why did these clusters fall only on the visible surface of the Moon, the side most prominent toward the Earth. It is difficult to explain. The most reliable proof of the "work" of meteorites would be to discover them on the lunar surface. However, meteorites and micrometeorites hit the Moon with cosmic speeds. Experiment and calculation show that one gram of meteorite material is capable, under these conditions, of exploding 2-3 orders of magnitude more /273 lunar rock material and crushing it, etc. In this process, particles of rock fly up at great speeds in a wide range. Some of them can leave the Moon, escaping their gravitational field, and appear on the Earth (for example, Eucrite). We must always remember this situation with the lunar balance of matter when we try to explain the formation of the regolith. However, some part, although very small, of the meteorite material remains on the surface of the Moon. We have given in this article preliminary data on finding meteorite material in the regolith. Undoubtedly it will be discovered. But it is still far from adequate for explaining the formation of the whole lunar regolith.

I would like to discuss something else. The most distinctive characteristic of the endogenous process of eruption of basaltic rocks on the Moon is their instantaneous contact with a high space vacuum. Magma on the Moon approaches the covering, and breaks through it. The liquid magma and its gases escape into a vacuum. Spraying of the liquid magma must occur, along with the loss, at great speed of its gases and other volatiles. Along with other tasks, we would like to find an explanation, by this endogenic route, for the origin of the regolith, having set up experiments accordingly. This is particularly true as the cardinal question about the balance of matter on the Moon is important for understanding the geochemical processes on the Earth, especially in the first billion years of its evolution.

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